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Title: SYSTEMS AND METHODS FOR FORMING AN OBJECT

Enclosed are the following papers, including those required to receive a filing date under 37 CFR 1.53(b):

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Enclosures:

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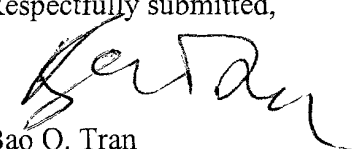
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Respectfully submitted,


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Enclosures

APPLICATION FOR UNITED STATES PATENT

in the name of

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of

Align Technologies, Inc.

for

**SYSTEMS AND METHODS FOR FORMING AN
OBJECT**

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SYSTEMS AND METHODS FOR FORMING AN OBJECT

BACKGROUND

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This invention relates to systems and methods for forming an object.

Mass customization is the application of mass production techniques to the production of parts that are different from each other and produced in rapid sequence. Mass-producing items that are generically similar to each other using production equipment that is rapidly modifiable or reprogrammable allows differences between these items.

One way to perform mass customization is to apply pressure forming to plastic materials. Current pressure forming technology uses convection, conduction and insolation to heat plastic for thermoforming. These methods are either 'bulk' heating with a homogeneous heating of the entire sheet, or are tailored for repeating the same process on one form; neither method is adaptable to custom heating control with different parts with mass production throughput. Current technology does not differentiate zones of different temperatures on the formed sheet in order to optimize the shape and thickness profile of the formed part, individually. Homogeneous heating allows the forming of material to draw (stretch) more on surfaces that are more parallel to the general direction of the forming draw, thus creating parts with widely varying thickness throughout. This result is often undesirable, as in the case of Orthodontic Aligners where 'bite' surfaces are thicker than other surfaces as a result. Current methods for controlling the heating profile are mechanically built-in and static, so they do not lend themselves to rapid process improvements, nor do they allow rapid re-programming for new shapes of thermoformed parts.

Thermoforming is a process of heating plastic sheet materials to their glass-transition temperature range, deforming them to a desired shape, then cooling them in order to set the new shape. A die, or solid form is used to define the 3D shape that the sheet will acquire as it transforms from a two-dimensional sheet when it is heated and forced to conform to the three-dimensional surface of the die. Transformation of the 2D sheet depends on its stretching around the die contours, thinning as it stretches. This stretching, in terms of where and how much, is dependent on localized stresses and

localized flexural modulus in the plastic; this action is interdependent between areas of the forming sheet so that stress distribution and modulus distribution define the final stretching and thickness distribution. If stress and modulus distribution are controlled, then stretching distribution can be controlled. The major determinant of forming stress is final shape and is controlled by the form of the die, so control of the modulus through temperature control will yield control of the thickness. Such control must account for the die shape and is admittedly complex, but is within the computational power of current computers and programs.

Flexural modulus is highly dependent on temperature. Control over localized temperature variation will result in control of stretching and thickness. As the sheet material is forming over the die, hotter areas will stretch more than cooler areas when all of these areas are within the glass-transition temperature range. This temperature/modulus control of areas will enable management of stretching within the distributed pattern of stresses, resulting in the control of thickness throughout the formed part.

SUMMARY

In one aspect, a method produces an object using thermal-forming by positioning a die representative of the object in a chamber; positioning a sheet of material over the die; pressurizing the chamber; and delivering a beam of energy over the sheet and the die to form the object.

Implementation of the method may include one or more of the following. The die can be placed on a moveable support. A seal can be positioned between the sheet and the chamber. Cool pressurized air can be circulated in the chamber after the object is formed. The die and the sheet can be aligned using one or more holes. Feedback data can be provided to a control system using a camera. A custom thermal pattern can be delivered over the sheet to optimize the forming of the object. A mirror can direct the beam onto the sheet and the die. The method can include receiving a digital representation of a target path; generating a mathematically smoothed version of the target path; applying the smoothed target path to generate a secondary target path; and generating a streamlined tool-path to fabricate the object. Relief data for the object can be merged with generic data to control the path of the beam.

In another aspect, a system produces an object using thermal-forming using a chamber adapted to receive a die representative of the object and a sheet of material; a pump to pressure the chamber; and a source of energy to deliver energy over the sheet and the die to form the object.

5 Implementations of the system can include one or more of the following. A moveable support can be used to suspend the die. One or more port valves can be used to circulate air after the object is formed. One or more markers can facilitate aligning the die and the sheet. A camera can be positioned in the chamber to provide feedback data. A controller can be programmed to generate a custom thermal pattern to optimize the forming of the object. The controller can also receive a digital representation of a target path; generate a mathematically smoothed version of the target path; apply the smoothed target path to generate a secondary target path; and generate a streamlined tool-path to fabricate the object. The controller can read relief data for the object and merge the relief data with generic data to control the path of the beam.

15 Advantages of the invention may include one or more of the following. The system is integrated into the pressure system of the thermo-former. This feature is important because this radiant laser heating of the formable plastic sheet develops an intentional thermal gradient with minimal thermal mass that is confined to the plastic sheet, so forming must occur immediately before the heat dissipates. This arrangement allows the forming to occur rapidly after the sheet is heated. Notice that the pressure system allows pressurized flow-through of gas; this allows cool air to be introduced to the formed sheet. The main purpose of this device is optimizing throughput of the forming process. The secondary reason for this device is enhanced process control for better definition of final thickness of formed parts. Finally, this device is very adaptable and lends itself to mass customization of pressure formed parts.

25 The techniques support rapid mass customization with rapid execution of data streaming, CAM calculations, and process device actions. The amount of data required by CAM for processing instructions to control material removal or modification machinery is reduced. The technique is advantageous for rapid workpiece changing situations that use dissimilar, but generically related shapes for workpieces and where the depth of action is not critical. Appropriate processes include cutting, surface

conditioning, trimming and welding with laser, plasma torch, and water jet as well as other projection-to-surface style devices.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is an elevational diagram showing the anatomical relationship of the jaws of a patient.

FIG. 2A illustrates in more detail the patient's lower jaw and provides a general indication of how teeth may be moved by the methods and apparatus of the present invention.

FIG. 2B illustrates a single tooth from FIG. 2A and defines how tooth movement distances are determined.

FIG. 2C illustrates the jaw of FIG. 2A together with an incremental position adjustment appliance.

FIG. 3 is a block diagram illustrating a process for producing incremental position adjustment appliances.

FIG. 4 shows an embodiment for paratherm forming an object such as a group of teeth on a dental arch.

FIGS. 5A-5B are exemplary illustrations of trimming operations using splines.

FIG. 6 is an exemplary illustration of a smoothed 3D spline and an ideal toolpath.

FIG. 7 is a flow chart illustrating a process for smoothing splines.

FIG. 8 is a block diagram illustrating a system for generating appliances in accordance with the present invention.

DESCRIPTION

FIG. 1 shows a skull 10 with an upper jaw bone 22 and a lower jaw bone 20. The lower jaw bone 20 hinges at a joint 30 to the skull 10. The joint 30 is called a temporal mandibular joint (TMJ). The upper jaw bone 22 is associated with an upper jaw 101, while the lower jaw bone 20 is associated with a lower jaw 100. A computer model of the jaws 100 and 101 is generated in accordance with the process of FIG. 3, and a computer simulation can model interactions among the teeth on the jaws 100 and 101. The computer simulation allows the system to focus on motions involving contacts

between teeth mounted on the jaws. The computer simulation allows the system to render realistic jaw movements that are physically correct when the jaws 100 and 101 contact each other. The model of the jaw places the individual teeth in a treated position. Further, the model can be used to simulate jaw movements including protrusive motions, lateral motions, and “tooth guided” motions where the path of the lower jaw 100 is guided by teeth contacts rather than by anatomical limits of the jaws 100 and 101. Motions are applied to one jaw, but may also be applied to both jaws. Based on the occlusion determination, the final position of the teeth can be ascertained.

Referring now to FIG. 2A, the computer model of the lower jaw 100 includes a plurality of teeth 102, for example. At least some of these teeth may be moved from an initial tooth arrangement to a final tooth arrangement. As a frame of reference describing how a tooth may be moved, an arbitrary centerline (CL) may be drawn through the tooth 102. With reference to this centerline (CL), each tooth may be moved in orthogonal directions represented by axes 104, 106, and 108 (where 104 is the centerline). The centerline may be rotated about the axis 108 (root angulation) and the axis 104 (torque) as indicated by arrows 110 and 112, respectively. Additionally, the tooth may be rotated about the centerline, as represented by an arrow 114. Thus, all possible free-form motions of the tooth can be performed.

FIG. 2B shows how the magnitude of any tooth movement may be defined in terms of a maximum linear translation of any point P on a tooth 102. Each point P1 will undergo a cumulative translation as that tooth is moved in any of the orthogonal or rotational directions defined in FIG. 2A. That is, while the point will usually follow a nonlinear path, there is a linear distance between any point in the tooth when determined at any two times during the treatment. Thus, an arbitrary point P1 may in fact undergo a true side-to-side translation as indicated by arrow d1, while a second arbitration point P2 may travel along an arcuate path, resulting in a final translation d2. Many aspects of the present invention are defined in terms of the maximum permissible movement of a point P1 induced on any particular tooth. Such maximum tooth movement, in turn, is defined as the maximum linear translation of that point P1 on the tooth that undergoes the maximum movement for that tooth in any treatment step.

FIG. 2C shows one adjustment appliance 111 which can be worn by the patient in order to achieve an incremental repositioning of individual teeth in the jaw as described generally above. The appliance is a polymeric shell having a teeth-receiving cavity, as described in U.S. Patent No. 5,975,893, entitled "Method and system for incrementally moving teeth," the full disclosures of which are incorporated by reference.

As set forth in the prior applications, each polymeric shell may be configured so that its tooth-receiving cavity has a geometry corresponding to an intermediate or final tooth arrangement intended for the appliance. The patient's teeth are repositioned from their initial tooth arrangement to a final tooth arrangement by placing a series of incremental position adjustment appliances over the patient's teeth. The adjustment appliances are generated at the beginning of the treatment, and the patient wears each appliance until the pressure of each appliance on the teeth can no longer be felt. At that point, the patient replaces the current adjustment appliance with the next adjustment appliance in the series until no more appliances remain. Conveniently, the appliances are generally not affixed to the teeth and the patient may place and replace the appliances at any time during the procedure.

The polymeric shell 111 can fit over all teeth present in the upper or lower jaw. Often, only certain one(s) of the teeth will be repositioned while others of the teeth will provide a base or an anchor region for holding the appliance 111 in place as the appliance 111 applies a resilient repositioning force against the tooth or teeth to be repositioned. In complex cases, however, multiple teeth may be repositioned at some point during the treatment. In such cases, the moved teeth can also serve as a base or anchor region for holding the repositioning appliance.

The polymeric appliance 111 of FIG. 2C may be formed from a thin sheet of a suitable elastomeric polymer, such as Tru-Tain 0.03 in, thermal forming dental material, available from Tru-Tain Plastics, Rochester, Minnesota. Usually, no wires or other means will be provided for holding the appliance in place over the teeth. In some cases, however, it will be desirable or necessary to provide individual anchors on teeth with corresponding receptacles or apertures in the appliance 100 so that the appliance can apply an upward force on the tooth that would not be possible in the absence of such an anchor.

FIG. 3 shows a process 200 for producing the incremental position adjustment appliances for subsequent use by a patient to reposition the patient's teeth. The flow chart of FIG. 3 is for purpose of explanation and does not necessarily reflect all possible paths of control flow in the execution of the client program.

As a first step, an initial digital data set representing an initial tooth arrangement is obtained (step 202). The initial data set may be obtained in a variety of ways. For example, the patient's teeth may be scanned or imaged using X-rays, three dimensional X-rays, computer-aided tomographic images or data sets, or magnetic resonance images, among others. The teeth data may be generated by a destructive scanner, as described in the incorporated-by-reference U.S. Application Serial No. 09/169,034, filed October 8, 1998. The initial data set is then manipulated using a computer having a suitable graphical user interface (GUI) and software appropriate for viewing and modifying the images. More specific aspects of this process will be described in detail below. Individual tooth and other components may be segmented or isolated in the model to permit their individual repositioning or removal from the digital model.

After segmenting or isolating the components, the teeth are moved based on rules and algorithms programmed into the computer. In this step, each stage of tooth movement is determined by an attraction model between selected points on adjacent teeth. This step is iterated until an acceptable result is achieved (step 206). In one embodiment, the system stops the movement when the relative positions of the teeth satisfy a predetermined target.

In step 206, positions for the upper and lower teeth in a masticatory system of a patient are determined by generating a computer representation of the masticatory system. An occlusion of the upper and lower teeth is computed from the computer representation; and a functional occlusion is computed based on interactions in the computer representation of the masticatory system. The occlusion may be determined by generating a set of ideal models of the teeth. Each ideal model in the set of ideal models is an abstract model of idealized teeth placement, which is customized to the patient's teeth, as discussed below. After applying the ideal model to the computer representation, the position of the teeth can be optimized to fit the ideal model. The ideal model may be

specified by one or more arch forms, or may be specified using various features associated with the teeth.

Once the teeth arrangements are determined, a series of appliances that move the teeth in a specified sequence are generated (step 208). For example, the teeth models may be rotated until their roots are in the proper vertical position. Next, the teeth models may be rotated around their vertical axis into the proper orientation. The teeth models are then observed from the side, and translated vertically into their proper vertical position. Finally, the two arches are placed together, and the teeth models moved slightly to ensure that the upper and lower arches properly mesh together. The meshing of the upper and lower arches together can be visualized using a collision detection process to highlight the contacting points of the teeth.

FIG. 4 shows an embodiment for paratherm forming an object such as a group of teeth on a dental arch. During manufacturing, a sheet of material such as plastic is placed over a physical model of an object to be produced. In one embodiment, the physical model is produced by a stereo-lithography apparatus (SLA). The sheet is heated in a thermo-former, using rapid moving optics to direct the energy beam of a heat source such as a laser onto the sheet prior to and/or during the application of pressure onto the sheet. Turning now to FIG. 4, a heat source such as a laser 300 generates a beam of energy that is projected through a beam expander 302 and a recollimating lens 303. The beam is then reflected by a mirror 304. The reflected beam hits on a sheet 312 that is placed proximate to a forming die 310 of a physical model of an object to be produced. In one embodiment, the sheet 312 is positioned between the beam and the die 310. An infrared (thermal) imaging camera 316, aimed at the plastic sheet 312, provides feedback data on heating performance. The thermal camera 316 provides a real-time feedback loop to a control system (not shown) by comparing the actual thermal profile with the CAM profile and making adjustments to laser parameters instantly or for process tuning and SPC. The camera output is also useful for process development.

The entire assembly is housed with a pressure plenum 320 having a top portion 322 and a die platen support portion 324. The pressure plenum (chamber) 320 provides a controllable volume of pressurized gas or air for forming the sheet 312 over the forming die 310. To contain the volume of pressurized gas or air, a plenum seal 326 is positioned

at the bottom of the top portion 322 and interfaces with the die platen support portion 324.

One or more ports 328-330 on the plenum allow flow-through of chilled pressurized gas that can accelerate the setting of the formed sheet. Additionally, this flow-through feature can be used for transporting hot gas across the sheet 312 during heating in order to retard convective heat dissipation from the sheet 312, thus enlarging the time 'window' for laser writing. The system uses separate volumes of heated and cooled gasses (and valves) that are not shown in FIG. 4. The system provides a very rapid sheet heating technique that should be complemented with fast forming and fast cooling for a short forming cycle.

The die platen support portion 324 is a porous support structure for the forming die(s) 310. The platen support portion 324 is adapted to move down to allow loading and unloading of plastic sheets in the forming position, and to allow exchange of dies. Then, the platen support portion 324 can move up with sufficient force to push the plastic sheet against the plenum seal and create a gas-tight boundary for pressure forming. Alignment features, such as pins, can be used to align the forming die so that CAM data can correlate laser-scanning geometry with die geometry. The motion of the platen and support is precise to maintain geometric integrity and sealing pressure.

In one embodiment, the plenum 320 contains laser optics, which alternately, could consist of a pressure chamber with an optical window for separating the optical components from the chamber. A laser generator is integrated with a pressure forming head. The system is controlled by a 2D beam directing system, CAM software, electronic part data and a control system.

The laser and optics direct light energy to the plastic sheet, heating it in a controllable manner. The laser, such as a carbon dioxide laser, produces a beam of invisible light that is mostly absorbed by many plastics, including visually transparent sheets; this absorption results in heating of the plastic that is locally proportional to the power density of the light at the surface of the plastic. Industrial lasers have a well-characterized energy profile across the beam, so optical manipulation of the beam can produce a custom, predictable heating pattern on plastic sheet. Optical, chemical and thermal properties within this process are predictable with computer programs. Likewise,

laser power and optical beam manipulation are controllable with computer programs. If laser power is adequate, a computer-controlled system can scan the plastic sheet rapidly enough to produce an appropriate pattern of heat that will not dissipate significantly before the forming cycle that follows. Such a scan might be completed within a second.

5 Rapid laser scanning allows the profiling a heat pattern because forming can occur before heat is dissipated. The forming pressure plenum is integrated with the heating source 300 so that the sequence of heating and forming can be very rapid or overlapping. This configuration allows an opportunity for forming before the plastic sheet cools to temperatures below the glass-transition point at any area of the sheet. The
10 large collimated laser beam allows the light energy profile to remain constant at different distances that the sheet may encounter during forming, so scanning while forming is viable on the surfaces that are most oblique to the laser beam.

Expansion and recollimation of the laser beam is desirable for heating a large area at any moment. The intrinsic Gaussian radiance profile of the laser is preserved and
15 spread with these optics, delivering energy rapidly with control over hot spots. This Gaussian delivery is optically tunable, so it provides control over the homogeneity of energy, much like an airbrush provides control over the scale and 'softness' of an artists brushstrokes. This technique enhances the versatility of 'writing' a thermal image to the plastic sheet by enabling broad warm areas to be filled and thinner hot areas to be defined
20 in rapid succession. Beam sizing is controlled by servo or manual adjustment of the recollimating lens using the axis of the divergent beam. This beam sizing could be computer controlled on-the-fly or done manually in process development, either method with the goal of keeping the heat of all areas of the plastic sheet within safe range of glass-transition temperatures. Dispersion of focused heat over time would be important
25 to consider when tuning the power and diameter of the laser beam. Alternatively, recollimation can be accomplished with a concave mirror 314 wherein beam sizing would be effected by adjustment of the beam expander 302 along the optical axis.

Fig. 4 shows an exemplary object 340, in this case an arch with teeth thereon, with a first pattern 342 derived from analysis data. A second pattern 344 is generated
30 using generic data, or template data. Further, a third pattern 346 is generated using relief data. Analysis data can be generated by an analysis program such as Finite Element

Analysis (FEA), Multi-physics Analysis, or Topographical programs. Program inputs, including sheet and die material and shape, are used to generate analysis data by computation. Analysis data is used to define process variables that pre-determine the thickness and stress distribution of the thermoformed part. Generic or template data is information common to a class of parts and related to thermoforming. This information is used to generate thermoforming process variables that require no change from part to part. Relief data is information about the shape of the forming die used for thermoforming. This information is presented as shapes, position and elevation of the part that correlate with temporal aspects of thermoforming a specific part. Surface shapes closest to the unformed sheet are deformed first. Forming progresses from the highest elevation toward the lowest elevation.

Directing the laser beam for scanning the thermal profile onto the plastic sheet is accomplished with a servo driven mirror (or galvo-mirror). Galvo mirrors pivot in two crossed axes under computer control, and are typically capable of deflecting a beam of light very rapidly and accurately.

A Computer-Assisted Manufacturing (CAM) program controls the mirror motion to 'write' the thermal pattern from a data file. CAM data, effectively processed with this device, can produce a two dimensional thermal image on the plastic sheet. Generation of CAM data can include several levels of sophistication, including any combination of the following: material temperature/modulus data, relief data (slice data), topological data, finite element analysis output, two-dimensional data and common template data. The purpose of processing this data is to generate a custom thermal profile on the plastic sheet so that the forming operation produces controlled thickness of the final part. For example, zones of the forming die that are closest to and most parallel with the plastic sheet are formed first, so they stretch least with homogeneous heating; heating these zones more than other zones will reduce local modulus and promote more local stretching (and thinning) in them. This method of localizing forming effects offers control over the strength, geometry and stress distribution in thermoformed parts.

After thermal forming, the objects or appliances need to be cut or trimmed. The processes described below generate toolpaths from geometric input to define automated motion of a computer-controlled device to trim objects such as appliances. The

application of this technique is more appropriate for complex, three-dimensional solid or surface geometry, both in reference to the toolpath and to the basic shape used to create the toolpath (i.e., the workpiece). However, the techniques can be applied to two-dimensional geometry as well.

5 Figs. 5A, 5B, 6 and 7 show embodiments applied to defined automated motion of a computer-controlled device to generate a physical model based on a dental arch. FIG. 5A shows a ribbon 400 surrounding an object 402. In this embodiment, the object 402 is a model of a dental arch of teeth. The ribbon 400 represents a toolpath for a trimming operation, and the teeth model represents complex geometry that the toolpath is
10 specifically generated for. The top edge of this ribbon 400 is a template or source spline 404 that is common to all toolpaths, whereas the bottom edge is the target spline, unique to each file that is downloaded to the CAM system. The template is a parametric table or form that can be customized to a specific object.

Information required to control the trim motion is contained in one or more ribbon
15 components, including the source spline or template 404, a target spline 406, synchronization points 410 on the source spline or template 404, and target points 408 on the target spline 406. The ribbon surface and synchronization lines may be inferred from spline data and synchronization data.

The source spline 404 works in conjunction with the target spline 406. A physical
20 or geometric relationship exists between the source spline 404 and the target spline 406 that defines a surface swept between the source spline 404 and the target spline 406. The geometric relationship is expressed as the tool path and represents the vectors for the tool. Exemplary vectors include the perimeter of a rotary tool such as a milling cutter or the center line of a beam of light from a laser or a beam of fluid from a water jet cutter.

25 During processing, synchronization lines 412 are projected from the synchronization point 410 to target point 408. The synchronization point 410 can be pre-established in position on the source spline or template 404. The target point 408 that correlates with the synchronization point 410 should be positioned on the target spline 406. In one embodiment, an orthogonal or plan view of FIG. 4A can be used to generate
30 orientations for synchronization lines 412 that appear as surface normals to the target spline 406. The direction for each projection is from the source spline (404) to the target

spline (406) and represents the equivalent of surface normals to the smoothed target spline 452 (mathematically smoothed 3D spline). The projection is done such that the synchronization lines 412 are substantially orthogonal to the mathematically smooth spline 452. The length of the surface normals is adjustable. Long normals tend to resemble the average more than short normals since angular changes from specific target splines change more radically with angular changes for short normals. Short normals tend to provide high resolution at the expense of more data having to flow through the CAM system. Alternatively, long normals would provide faster motion at the expense of precision and resolution because the angular changes have to be accurately controlled.

The template takes common information required for the CAM process as a standard for all cases in mass customization. By applying a relatively simple set of data that represents the differences between all of the different parts, the template 404 can be adapted for each object 402 to customize the output. The information embodied in the template may be streamlined. One optimization removes CAM calculations that are based on specific solid geometry from the toolpath generation process. In such an optimization, surface undulations are ignored. The optimization of tool head velocity can be achieved by minimizing the number, magnitudes and durations of accelerations because these parameters have deleterious effect on average velocity. The template minimizes these degradations of toolpath motions by ignoring their source.

In one embodiment, one or more generic files are categorized so that similar shapes are defined within parametric limits such as size or shape within a superset; for example, small dental arches are distinguished from large arches. In one implementation, code can be provided in the file for calling the template 404. In another embodiment, a hierarchical format is used to enhance the adaptability of CAM to fit a wide range of shapes that a specific process would be applied to; for example, modification of bone implants for different types of bones. The source spline shape and other parametric data can be grouped under headings or subheadings.

FIG. 5B is another view of FIG. 5A. FIG. 5B shows the object 402 resting on a support 430. FIG. 5B also shows a smooth path 432 for the motion of the system of the laser 404. In the exemplary embodiment of FIG. 5B, trim vectors 420 are approximately forty degrees relative to object surface normals. The object 402 bears a generalized

relationship to the surface normals so that the angle is constant in this example. The surface normals of FIG. 5B follow a predetermined formula that is based on an idealized model of the object 402.

The motion system of Figs. 5A and 5B follows the tool path has a motion that is generally smooth and constantly leading. As the motion system follows the source spline 404 or an equivalent of the source spline 404, its motion is smooth. Further, any vectors that relate to a position at any moment in time of the motion system at 404 as it moves forward also relates to a forward motion along the target spline (408). Thus, a correlated move generally exists in the forward direction between the motion system and the target object itself.

FIG. 6 shows in more detail the relationship between an idealized tool-path 450 and a mathematically smoothed spline 452. A transition or translation process mathematically converts the idealized tool path 450 into a spline 452 that is a mathematically smoothed 3D spline. The mathematically smoothed spline generally follows a monotonic curvature in all three dimensions. The mathematically smoothed 3D spline is used in an intermediate step that generates a set of synchronization lines which are all the same length and which have been adjusted specifically so that the other ends of the synchronization line are connectable together by another 3D spline that becomes a source spline. The mathematically smoothed spline is provided to a CNC controller that generates a smooth tool path and drives the tool head motion itself. An end-effector of the tool can articulate around the target object using a numerically controlled (NC) axis or rotary axis that changes the vector from any given points along the source spline 404.

In FIG. 6, synchronization lines 412 that descend from the top spline to the bottom spline are representative of the direction (vector) of the trim beam or tool axis at different positions around the path. The CAM interpolates the toolpath between synchronization lines. Due to the interpolation, the resulting motion of the source device (laser motion devices) is smooth and progressive without sharp turns or reversals. In embodiments where the source device is a laser or projected beam device where effective focus occurs with substantial focal depth, the source device does not need to track the target along the axis of the trim beam, even though the target spline articulates in this beam-axis direction.

FIG. 7 shows a process 450 to generate a smoothed spline for trimming an object. The smoothing of a spline such as a source spline first requires the creation of an ideal model surface or solid shape (step 452). In an embodiment, the ideal model surface or shape can be a 3D statistical mean. In another embodiment, the ideal surface or solid shape may represent all individual models, a dental arch in this example. After this ideal model is created, the process 450 creates an idealized toolpath (step 454). The idealized toolpath can consist of a 3D spline that is anchored to the surface of the model. This toolpath may follow a surface feature such as the gum line of this dental model, or follow a design feature. Next, the process 450 generates a (mathematically) smooth 3D spline using the idealized toolpath (equivalent to the target spline) from the ideal model surface (step 456). The process 450 then generates surface normals from the ideal model surface at points distributed around the idealized toolpath (step 458). These surface normals should be the same length, preferably matching the distance from the closest rotary axis of the motion system. Elevate or lower these normals by a consistent angle, if required; the example shows 40-degree elevation. The process 450 then displaces each surface normal from its end to the nearest point on the smooth 3D spline (step 460). Step 460 displaces the surface normals from the idealized spline which is rather curvy into the mathematically smoothed 3D spline to create a set of surface normals or synchronization lines that have an angular relationship to the surface normals. The endpoints are connectable with the smooth spline that then in turn creates the source spline.

A spline is created that connects each unattached end of all the surface normals sequentially in a loop (step 462). This spline will be the source spline that will define motion of the tool head by defining tool orientation vectors, and subsequent motion of the tool head itself. If this source spline is not smooth, it may be adjusted (step 464). In one embodiment, the adjustment includes a moderate elevation or lowering of the angle of each surface normal using the target spline intersection as a pivot axis, and alteration of the source spline. This adjustment will beneficially affect streamlining of the tool head motion and action of the tool on the surface of the workpiece.

The smoothed spline generated using the process 450 is then used to cut or trim the object. The source spline data is loaded as part of a template of a computer aided manufacturing (CAM) system. This makes the CAM system capable of accepting

specific target spline data as a complement that fulfills most data requirements needed to generate a specific toolpath. The template can include data requirements, and part orientation information for fixturing the workpiece must be included in the template to assure the correlation of geometry between the device toolpath and the workpiece during operation. Part orientation is established with a three-axis Cartesian datum that is common between the ideal model and all specific models. Additional common data incorporated in the template may include other process parameters such as motion velocities, effector power (flow rate, flow velocity, focus, etc.), temperature, and pulse rate. The template can also include algorithms for adjustment of process parameters that are triggered by special geometric conditions of the target spline or by special notation attached to the target spline file.

The target spline data is also loaded into the CAM system to generate coded instructions for the motion controller. This data describes the 3D spline and its reference datum. Additional information may be added for assisting control through the CAM program in a manner that distinguishes the specific file model from the ideal model, including part querying and verification of a match through machine vision or other similar means.

FIG. 8 is a simplified block diagram of a data processing system 500 for handling CAM operations. Data processing system 500 typically includes at least one processor 502 that communicates with a number of peripheral devices over bus subsystem 504. These peripheral devices typically include a storage subsystem 506 (volatile memory subsystem 508 and file storage subsystem 514), a set of user interface input and output devices 518, and an interface to outside networks 516, including the public switched telephone network. This interface is shown schematically as "Modems and Network Interface" block 516, and is coupled to corresponding interface devices in other data processing systems over communication network interface 524. Data processing system 500 may include a terminal or a low-end personal computer or a high-end personal computer, workstation or mainframe. The user interface input devices typically include a keyboard and may further include a pointing device and a scanner. The pointing device may be an indirect pointing device such as a mouse, trackball, touchpad, or graphics tablet, or a direct pointing device such as a touchscreen incorporated into the display.

Other types of user interface input devices, such as voice recognition systems, may be used. User interface output devices may include a printer and a display subsystem, which includes a display controller and a display device coupled to the controller. The display device may be a cathode ray tube (CRT), a flat-panel device such as a liquid crystal display (LCD), or a projection device. The display subsystem may also provide nonvisual display such as audio output.

Storage subsystem 506 maintains the basic programming and data constructs that provide the functionality of the present invention. The software modules discussed above are typically stored in storage subsystem 506. Storage subsystem 506 typically comprises memory subsystem 508 and file storage subsystem 514. Memory subsystem 508 typically includes a number of memories including a main random access memory (RAM) 510 for storage of instructions and data during program execution and a read only memory (ROM) 512 in which fixed instructions are stored. In the case of Macintosh-compatible personal computers the ROM would include portions of the operating system; in the case of IBM-compatible personal computers, this would include the BIOS (basic input/output system). File storage subsystem 514 provides persistent (nonvolatile) storage for program and data files, and typically includes at least one hard disk drive and at least one floppy disk drive (with associated removable media). There may also be other devices such as a CD-ROM drive and optical drives (all with their associated removable media). Additionally, the system may include drives of the type with removable media cartridges. The removable media cartridges may, for example be hard disk cartridges, such as those marketed by Syquest and others, and flexible disk cartridges, such as those marketed by Iomega. One or more of the drives may be located at a remote location, such as in a server on a local area network or at a site on the Internet's World Wide Web. In this context, the term "bus subsystem" is used generically so as to include any mechanism for letting the various components and subsystems communicate with each other as intended. With the exception of the input devices and the display, the other components need not be at the same physical location. Thus, for example, portions of the file storage system could be connected over various local-area or wide-area network media, including telephone lines. Similarly, the input devices and display need not be at the same location as the processor, although it is anticipated that

the present invention will most often be implemented in the context of PCS and workstations. Bus subsystem 504 is shown schematically as a single bus, but a typical system has a number of buses such as a local bus and one or more expansion buses (e.g., ADB, SCSI, ISA, EISA, MCA, NuBus, or PCI), as well as serial and parallel ports.

- 5 Network connections are usually established through a device such as a network adapter on one of these expansion buses or a modem on a serial port. The client computer may be a desktop system or a portable system.

Scanner 520 is responsible for scanning casts of the patient's teeth obtained either from the patient or from an orthodontist and providing the scanned digital data set
 10 information to data processing system 500 for further processing. In a distributed environment, scanner 520 may be located at a remote location and communicate scanned digital data set information to data processing system 500 over network interface 524. Fabrication machine 522 fabricates dental appliances based on intermediate and final data set information received from data processing system 500. In a distributed environment,
 15 fabrication machine 522 may be located at a remote location and receive data set information from data processing system 500 over network interface 524.

The computer system 500 receives specific geometric data or in this case specific 3D spline target data and produces an output that is understandable by a controller 521. The controller 521 interprets computer code from the computer 500 into instructions for
 20 electromechanical actuators such as motors, for example. The instructions specify acceleration ramps, velocities, changes in velocities, pulse rate, the relationship between certain motions or timing sequence and the different axes. In one embodiment with five axis, five different motors, three motors describing X, Y and Z motion and two motors describing rotary motion about two of the axes.

25 Various alternatives, modifications, and equivalents may be used in lieu of the above components. The commercial manifestation of the concept of templates could take different forms. One form might be as an algorithm or subprogram within CAM. Another form could be as a separate program that would work with a variety of CAM programs. A third option would be as proprietary software, developed and used
 30 internally within a company. It should be noted that this invention, if patented, would have no practical enforceability outside the commercial forms. Development of software

within a company for application within that company cannot be controlled outside that company; this fact makes strong development of a commercial format attractive.

While the invention has been shown and described with reference to an embodiment thereof, those skilled in the art will understand that the above and other
5 changes in form and detail may be made without departing from the spirit and scope of the following claims.

What is claimed is:

008270-26792960

1. A method for producing an object using thermal-forming, comprising:
positioning a die representative of the object in a chamber;
positioning a sheet of material over the die;
pressurizing the chamber; and
5 delivering a beam of energy over the sheet and the die to form the object.

2. The method of claim 1, further comprising placing the die on a moveable support.

10 3. The method of claim 1, further comprising placing a seal between the sheet and the chamber.

15 4. The method of claim 1, further comprising circulating cool pressurized air after the object is formed.

5. The method of claim 1, further comprising aligning the die and the sheet.

20 6. The method of claim 1, further comprising providing feedback data to a control system using a camera.

7. The method of claim 1, further comprising delivering a custom thermal pattern to optimize the forming of the object.

25 8. The method of claim 1, further comprising providing a mirror to direct the beam onto the sheet and the die.

30 9. The method of claim 1, further comprising:
receiving a digital representation of a target path;
generating a mathematically smoothed version of the target path;
applying the smoothed target path to generate a secondary target path; and
generating a streamlined tool-path to fabricate the object.

10. The method of claim 1, further comprising reading relief data for the object and merging the relief data with generic data to control the path of the beam.

5 11. A system to produce an object using thermal-forming, comprising:
A chamber adapted to receive a die representative of the object and a sheet of material;
A pump to pressure the chamber; and
A source of energy to deliver energy over the sheet and the die to form the object.

10 12. The system of claim 11, further comprising a moveable support to suspend the die.

15 13. The system of claim 11, further comprising a seal positioned between the sheet and the chamber.

14. The system of claim 11, further comprising one or more port valves to circulate air after the object is formed.

20 15. The system of claim 11, wherein each die further comprises one or more markers to facilitate aligning the die and the sheet.

25 16. The system of claim 11, further comprising a camera positioned in the chamber to provide feedback data.

17. The system of claim 11, further comprising computer-readable code to generate a custom thermal pattern to optimize the forming of the object.

30 18. The system of claim 11, further comprising a mirror to direct the beam onto the sheet and the die.

19. The system of claim 11, further comprising computer readable code to:
receive a digital representation of a target path;
generate a mathematically smoothed version of the target path;
apply the smoothed target path to generate a secondary target path; and
generate a streamlined tool-path to fabricate the object.

20. The system of claim 11, further comprising computer readable code to read relief data for the object and merge the relief data with generic data to control the path of the beam.

ABSTRACT

5

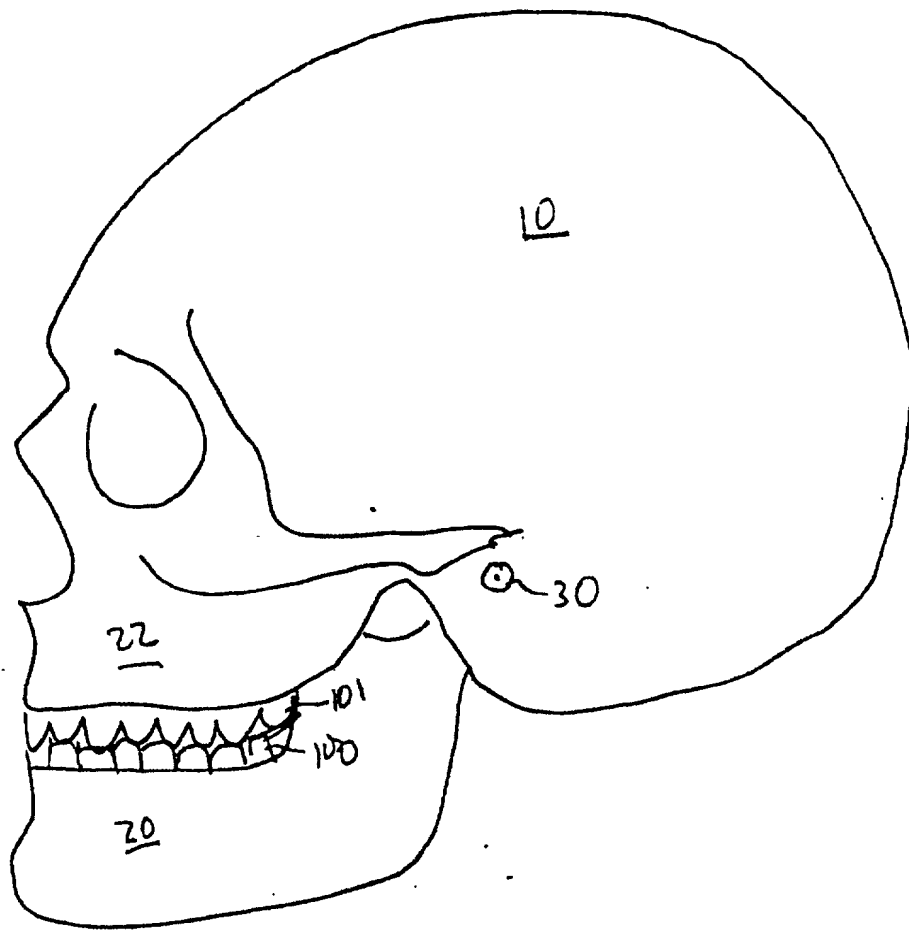


FIG. 1

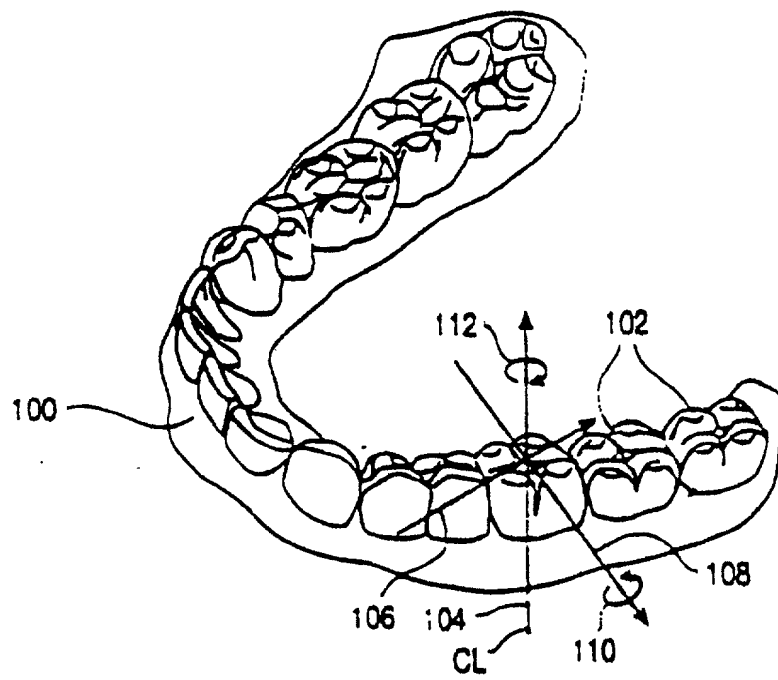


FIG. 2A

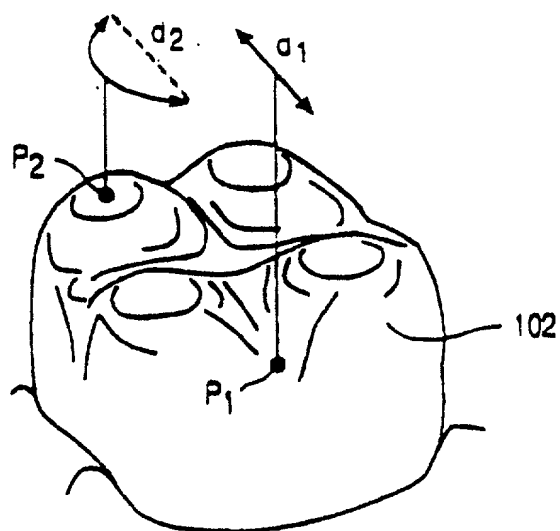


FIG. 2B

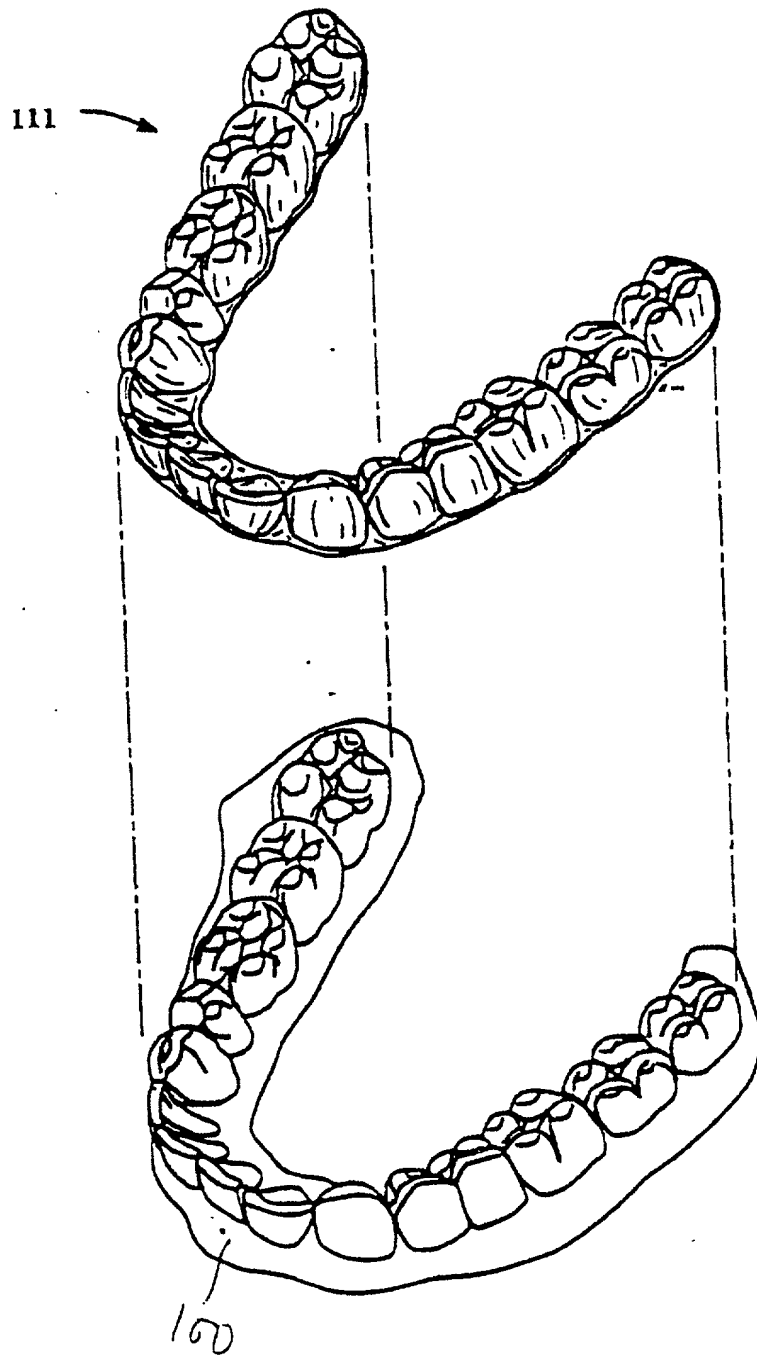


FIG. 2C

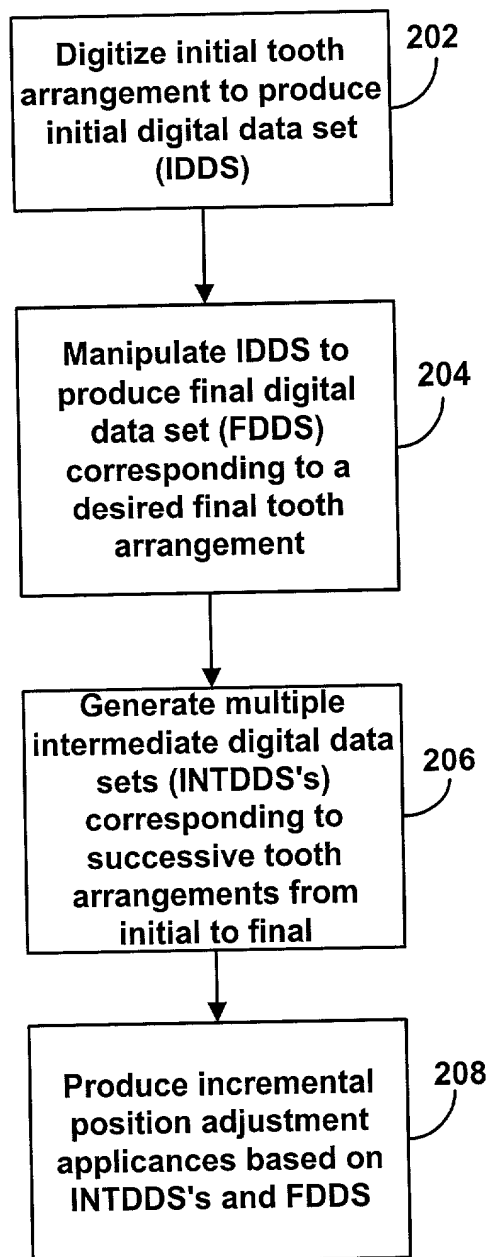
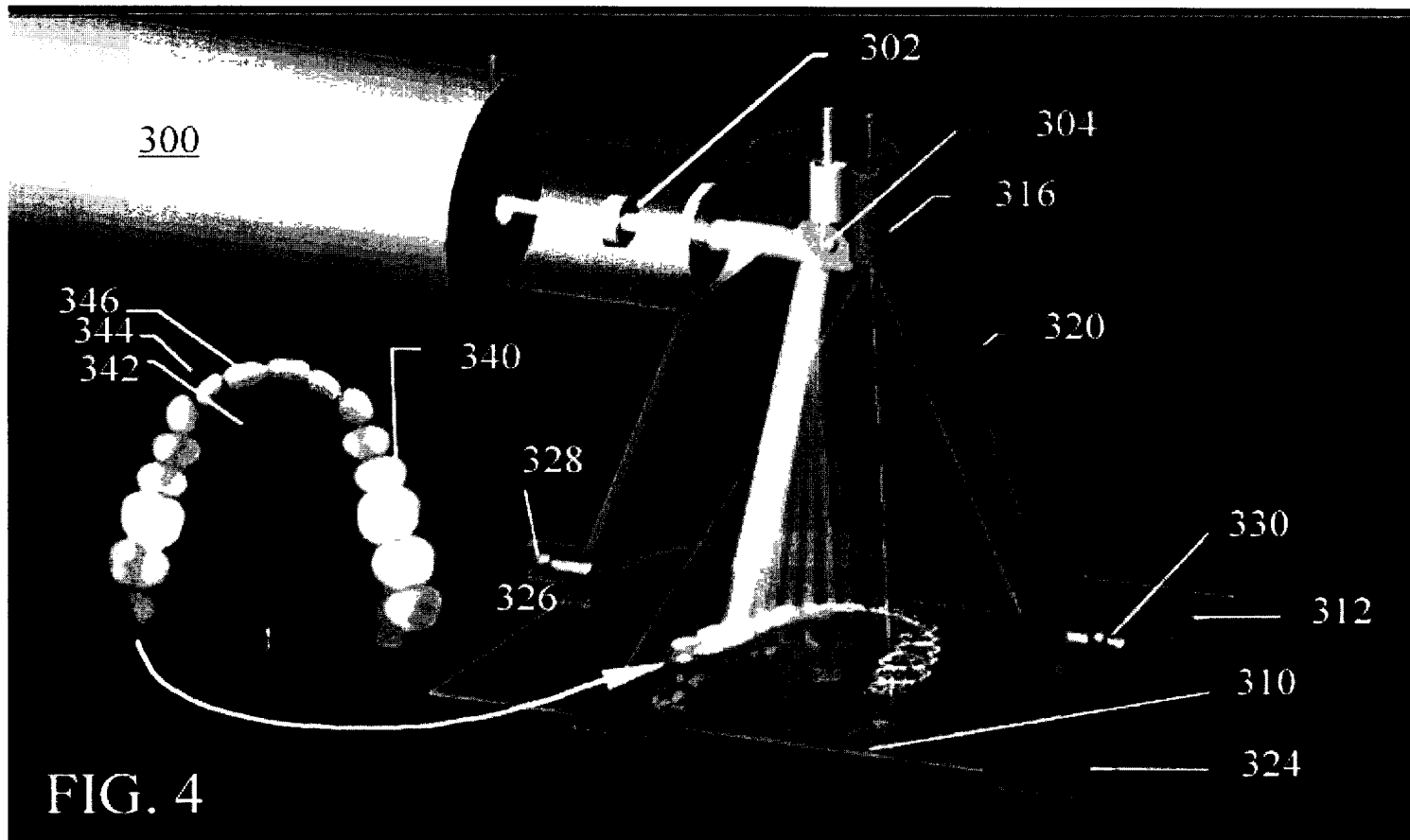
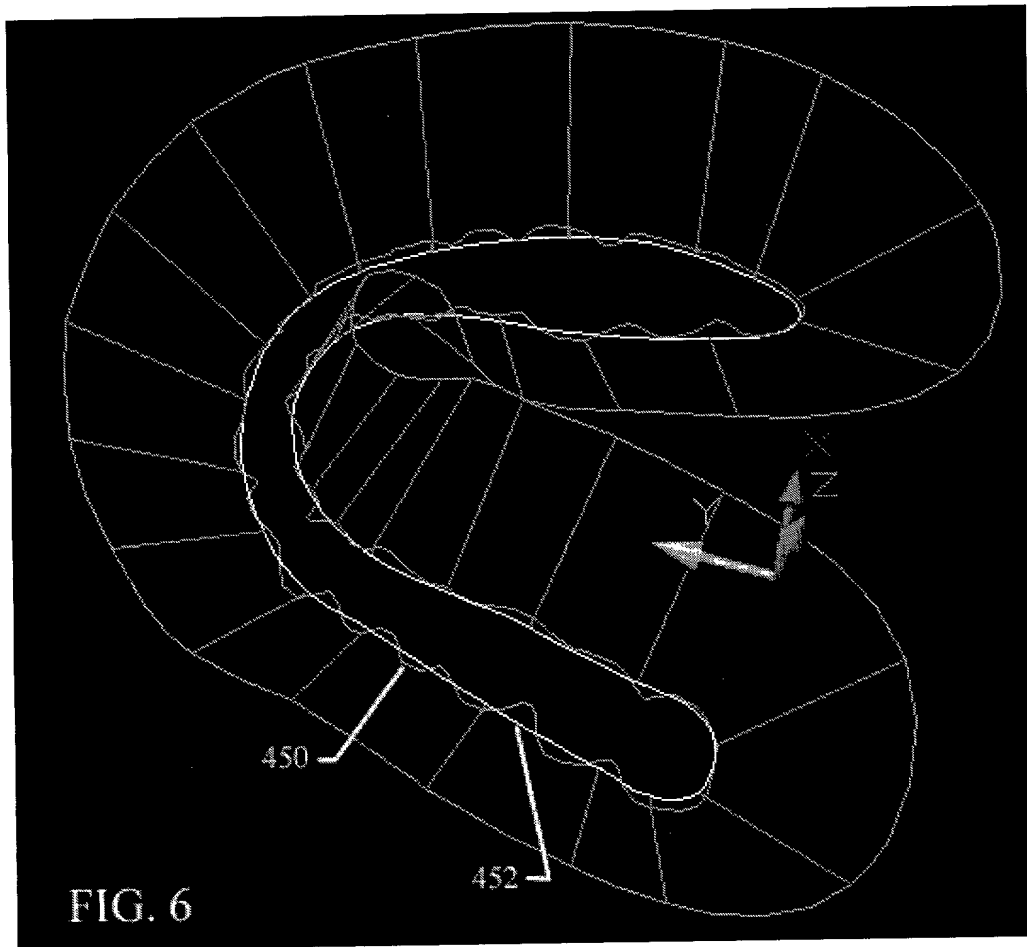


FIG. 3





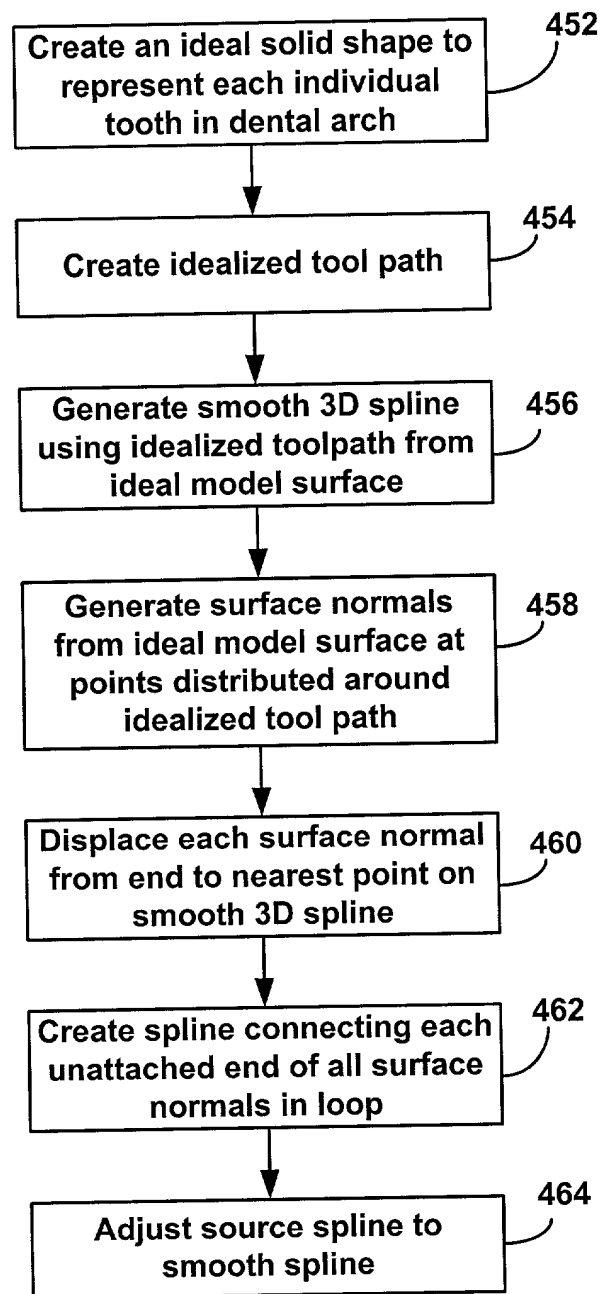


FIG. 7

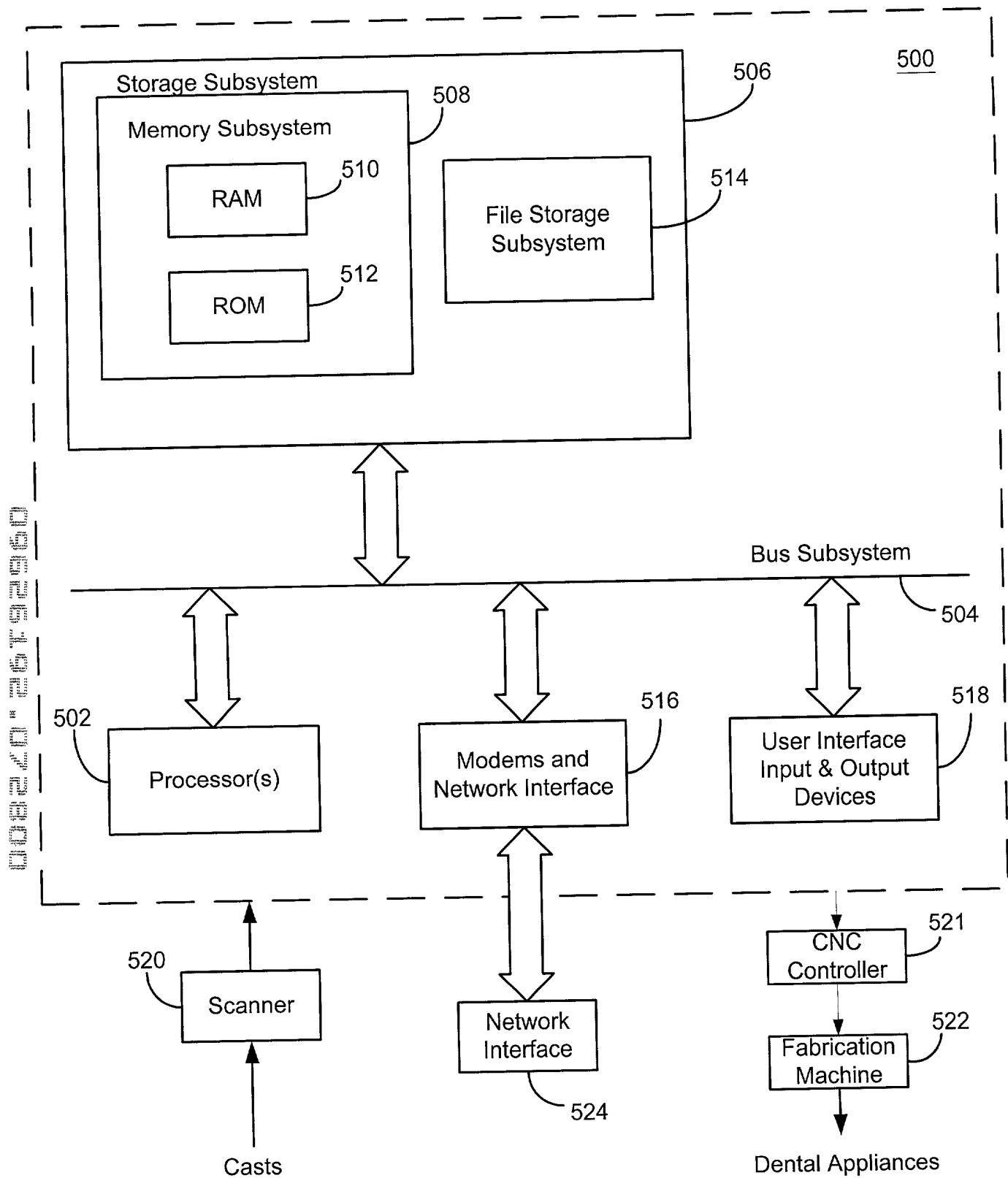


FIG. 8

COMBINED DECLARATION AND POWER OF ATTORNEY

As a below named inventor, I hereby declare that:

My residence, post office address and citizenship are as stated below next to my name,

I believe I am the original, first and sole inventor (if only one name is listed below) or an original, first and joint inventor (if plural names are listed below) of the subject matter which is claimed and for which a patent is sought on the invention entitled SYSTEMS AND METHODS FOR FORMING AN OBJECT, the specification of which:

☒ is attached hereto.

☐ was filed on _____ as Application Serial No. _____.

☐ was described and claimed in PCT International Application No. _____ filed on _____ and as amended under PCT Article 19 on _____.

I hereby state that I have reviewed and understand the contents of the above-identified specification, including the claims, as amended by any amendment referred to above.

I acknowledge the duty to disclose all information I know to be material to patentability in accordance with Title 37, Code of Federal Regulations, §1.56.

I hereby appoint the following attorneys and/or agents to prosecute this application and to transact all business in the Patent and Trademark Office connected therewith:

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Customer No. 24710

I hereby declare that all statements made herein of my own knowledge are true and that all statements made on information and belief are believed to be true; and further that these statements were made with the knowledge that willful false statements and the like so made are punishable by fine or imprisonment, or both, under Section 1001 of Title 18 of the United States Code and that such willful false statements may jeopardize the validity of the application or any patents issued thereon.

Full Name of Inventor: BARRY A. SIMKINS

Inventor's Signature: _____

Date: _____

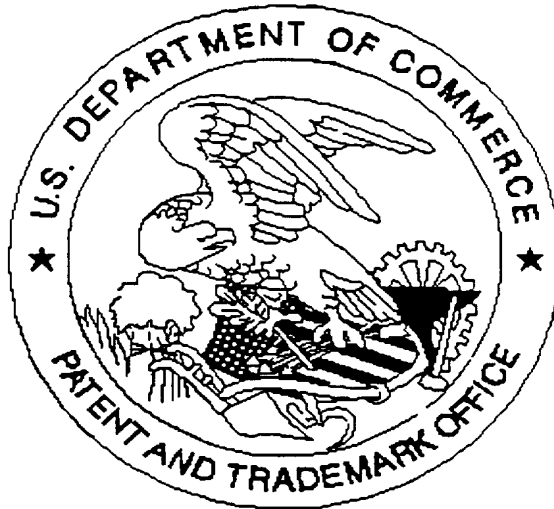
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